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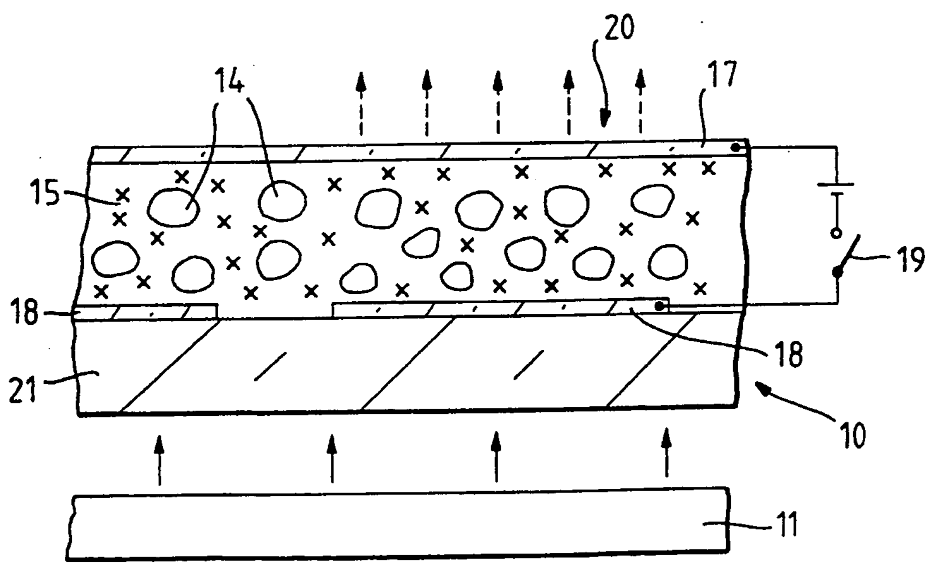
(54) **Liquid crystal display devices**

(57) In an LC display device of a known type having droplets of LC material 14 carried in a polymer matrix material 15 enclosed between electrodes 17, 18 to define a plurality of display elements 20 controlling the passage of light from a source 11 through the display device, the polymer matrix contains a light absorbing dye for improving the display contrast, and picture resolution. Display elements formed at the intersections of orthogonal electrodes 17, 18 selectively transmit or scatter light in dependence upon the presence or absence of an applied field, and the scattered light is substantially absorbed by passage through the dye material. The dye may be of a neutral or a desired colour. Dye may also be added to LC droplets for additional absorption or for colouring. An optical projection system may include a plurality of LC devices operating in a respective primary colour in combination with lenses, beam splitters and combiners.

Fig. 1.



At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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Fig. 1.

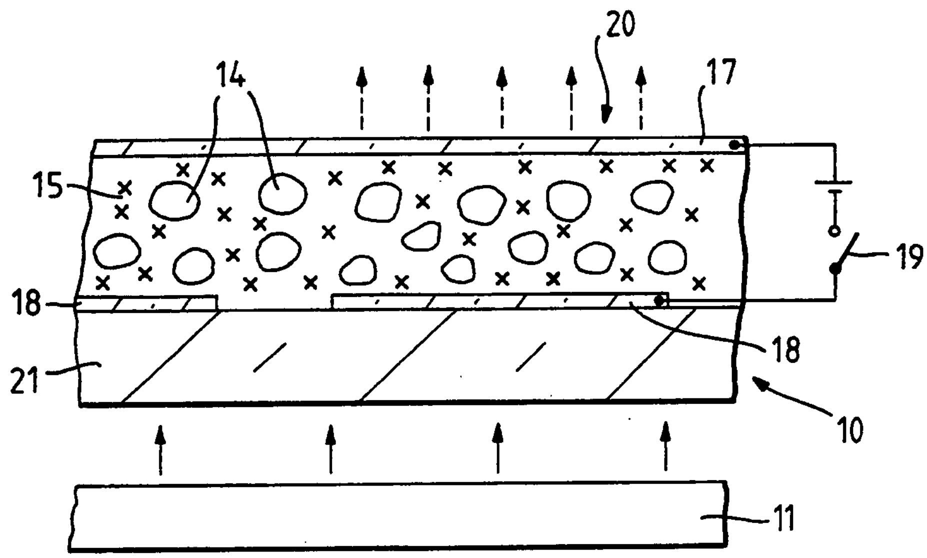
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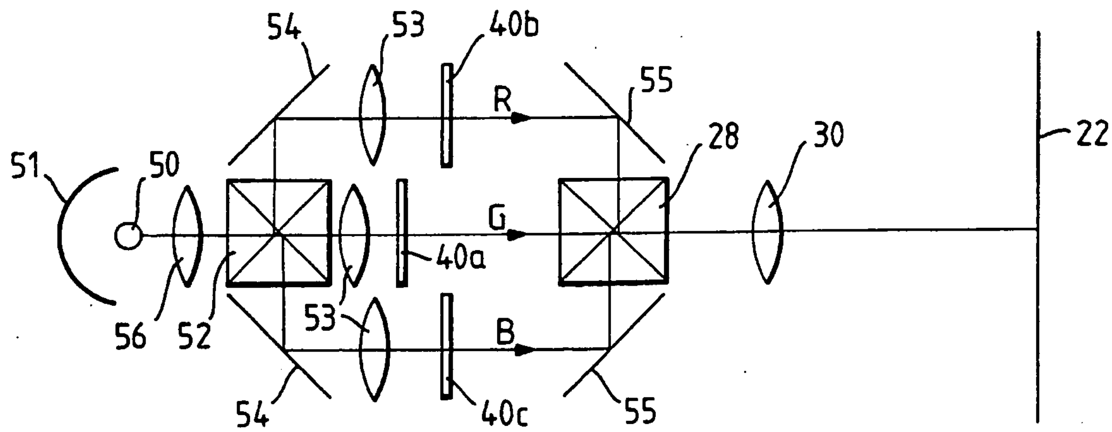
Fig. 2.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DESCRIPTION

LIQUID CRYSTAL DISPLAY DEVICES AND PROJECTION SYTEMS USING SUCH DEVICES

This invention relates to a liquid crystal display device having a liquid crystal panel comprising droplets of liquid crystal material carried in a polymer matrix and electrodes on opposing sides therof defining a plurality of display elements, and means for illuminating the panel from one side, the display elements being operable to control the passage therethrough of light from the illumination means in a viewing direction at the other side so as to produce a display effect.

The invention relates also to a projection display system using such a device.

Liquid crystal display panels of the above kind are commonly referred to as polymer dispersed liquid crystal devices or encapsulated liquid crystal film devices. Examples of such devices are described in EP-A-88126, and in the article entitled "Polymer Encapsulated Nematic Liquid Crystals for Display and Light Control Applications" by J. L. Fergason published in SID 85 DIGEST at pages 68-69. Briefly, they consist of small droplets of liquid crystal (LC) material, typically of the nematic type in operation and having positive dielectric anisotropy, embedded in a solid polymer film. When light enters the film it is scattered at the interfaces between the polymer and the LC by an amount which depends on the difference in refractive indices, and, as the LC material is birefringent, also on the orientation of the LC relative to the direction of the light and the direction of polarisation of the light. If the refractive index of the polymer is chosen to be close to the "ordinary" refractive index (i.e. the refractive index perpendicular to the director) of the LC, then very little light is scattered when the light is parallel to the crystal axis. When a sufficient voltage is applied across the film, the LC droplets align perpendicular to the film surface. In this condition, light that enters perpendicular to the film surface suffers very little scattering,

with the amount of scattering increasing as the angle of the light departs from perpendicular. On the other hand, when no voltage is applied, the orientation of the LC axes is random and maximum scattering occurs.

The nature of these liquid crystal panels renders them advantageously suited to a variety of applications. They can be flexible and of large area compared with conventional liquid crystal panels. In one application, the panel comprises a number of separate, individually operable areas functioning as light shutters to provide a display effect, examples of which are given in the aforementioned article by Fergason.

When used with a light source directing light onto one side of the panel, transmission of light through the panel is determined by operation of the individual areas, or display elements, so that when viewed from the other side the visible effects of elements which serve to transmit light and elements which serve in effect to block light by scattering combine to produce a display. Display elements which are energised, that is, across which a voltage is applied, have aligned or partially aligned LC droplets and allow light to be transmitted substantially directly through the panel to the viewing side. For suitably high applied voltages resulting in aligned droplets, virtually no reflection or change in direction of the light occurs so that a comparatively high light output is produced at that element whilst unenergised elements have unaligned LC droplets and appear relatively dark in comparison to a viewer viewing the panel output from the side opposite the light source. Using lower applied voltages partial alignment is achieved producing grey tones. An explanation of the behaviour of the film in response to the application and renewal of electric fields is provided in above-mentioned EP-A-88126 and in the article by S. Zumer et al entitled "Light scattering from a small nematic droplet" published by The American Physical Society in Physical Review Vol. 34, No. 4, October 1986 at pages 3373 to 3386 to which reference is invited for further

information in this respect.

The panel has an important advantage over conventional twisted nematic liquid crystal display panels in that polarised light is not required. Due to the absence of polarisers, the brightness of display possible from this kind of device is potentially twice that of a conventional LC device employing polarisers. This advantage would seem to make them attractive for use in a projection display system in which the light output from the panel is projected via a projection lens onto a viewing screen as well as for direct view use. However, the performance of such devices, particularly in projection systems, has failed to meet expectations in that satisfactory contrast ratios have not been achievable. In a projection system, the contrast depends on the ratio of the light collected when the liquid crystal droplets are aligned with the direction of the light, i.e. in transmission mode with energising voltage on, to the light collected when the droplets are not aligned, voltage off, and are fully scattering.

It is an object of the present invention to provide an LC display device of the above-described type which offers improved contrast performance.

It is another object of the present invention to provide a projection display system including such a device in which an improved contrast ratio is obtainable.

According to one aspect of the present invention, a display device of the kind referred to in the opening paragraph is characterised in that the polymer matrix contains a light absorbing dye. Such a display device provides by virtue of the absorbing dye a much improved contrast ratio and also an increase in resolution capability. Superior performance, for example in direct view operation, is thus obtained.

According to another aspect of the invention, there is provided a projection display system including a liquid crystal display device in accordance with the one aspect of the present invention and a projection lens disposed on the opposite side of

the panel to the illuminating means for projecting the output from the panel onto a screen. A notable improvement in display image quality can be expected by virtue of the enhancement of contrast and resolution afforded by the absorbing dye.

To obtain a reasonable contrast ratio in a projection system, a small aperture illumination system needs to be combined with a small aperture projection lens. This follows from a consideration of the optical characteristics of the projection system. The apertures of the illumination system and projection lens are important parameters as they not only affect contrast ratio but also display picture brightness. Theoretically possible contrast ratios in a projection system can be calculated if scattering patterns are known. However, optical scattering is a complex subject, as will be apparent from the aforementioned article by Zumer et al. The distribution of the scattered light is very dependent on the difference between the refractive indices of polymer and the "extraordinary" direction of the LC. Unless this difference is large, the scattering pattern will have a forward direction bias. The number and size of the LC droplets is also an important consideration. For simplicity, it will be assumed for the following discussion that the known form of polymer dispersed liquid crystal panel scatters uniformly in its unenergised state. Since it is planar, uniform scattering can be interpreted as producing a cosine (or Lambertian) light distribution in both forward and backward directions, with reference to the direction of illumination. If light from the panel is collected over a solid angle with semi-aperture alpha, then the fraction of light collected is proportional to the square of the sine of alpha. Assuming also that the solid angle of light incident on the panel is sufficiently small that light lost by scattering in the energised state is negligible, then under these conditions alpha must not exceed approximately eight degrees if a contrast ratio of 100:1 is to be achieved. In optical terms, this implies an aperture of f/3.5. This applies only for a uniform scattering situation. Worse contrast ratios

will be obtained where scattering produces more light in the forward direction than in the backward direction, as appears to be the case in practice with known devices. For high contrast ratios, therefore, it is necessary to have a projection optical system with an aperture smaller than f/3.5, whereas an aperture of around f/2 has been found suitable in projection displays using conventional LC display panels. Consequently, the brightness of the system using a known type of polymer dispersed LC panel is potentially less than for other systems, even allowing for the gain resulting from the absence of polarisers.

The incorporation of absorbing dye in the matrix in accordance with the invention has the effect of reducing the light intensity in the scattering state. Scattered light travels, on average, much further through the polymer material than non-scattered light and so should suffer much greater losses, even for light which eventually emerges from the panel near the normal in a forward direction. Inevitably, some small loss of brightness will occur in the transmissive, energised, state as light has to travel through the polymer intermediate the LC droplets. Even so, the beneficial increase in constrast achieved at the expense of a small reduction in brightness is considerable. As an example, the loss to direct light need be no more than 10-20% whereas the resulting loss to the scattered light can be from 50-80%, giving a useful contrast ratio gain.

The provision of a light absorbing dye in the polymer offers a further important advantage. When a display element of the panel is energised and in its scattering state, light can travel in a sideways direction, i.e. within the plane of the panel, towards adjacent display elements. The absorbing dye assists in reducing the intensity of this light. Consequently obtainable resolution is improved as less unwanted light is capable of emerging from adjacent display elements.

It is already known to incorporate a pleochroic dye in the liquid crystal droplets of a polymer dispersed LC display panel in order to increase absorption characteristics. However,

besides being relatively expensive and requiring careful use, absorption of the dye is not zero in the energised state. Panels using pleochroic dye in this manner tend to exhibit relatively low contrast.

In EP-A-121415 there are described encapsulated liquid crystal display arrangements in which a dye may be added to the matrix material and/or the liquid crystal droplets for light colouring purposes. The displays are of a direct view type which operate in a different manner to the kind of device with which the present invention is concerned in that a bright, coloured, light output is produced in response to non-energisation by scattering whereas a darker output is produced in response to energisation through absorption. The display elements do not act as simple electro-optic light shutters which transmit light directly from the light source to the other side in the field of view direction when the LC material is in its ordered alignment, energised, state and which block light when in the opposite, random alignment, state.

The panel used in the present invention may be of any known type, that is, for example, of the type in which LC crystal material is contained in polymer shell or capsule which in turn is embedded in matrix material or alternatively of the type in which droplets of LC material are dispersed directly in the matrix material. The matrix material can be, for example, PVA, latex, gelatin, epoxy or other resin.

The light absorbing dye contained in the matrix material can be of any suitable kind which is compatible with the matrix material. Suitable dyes will be readily apparent to persons skilled in the art. It is preferable that the dye is soluble in the matrix material so to to avoid the possibility of precipitation and to enable desired distribution to be achieved conveniently. The concentration of the dye, dependent on the type of dye, does not have to be high as beneficial effects will result using only modest concentrations.

The absorbing dye is selected to absorb the colour or

colours of light emitted from the light source or supplied to the panel from the light source. For example, in the case where the panel is illuminated with white light, the dye may comprise a substantially neutral dye.

For a projection system comprising three liquid crystal display devices each of which is illuminated by light substantially of a respective, primary, colour the absorbing dye used in each panel may be substantially neutral and/or a respectively coloured absorbing dye. In known projection systems, trimming filters are sometimes provided either before or after the panels to increase the colour gamut by trimming the spectral transmission. The need for such trimming filters is avoided by using a coloured absorbing dye which serves to remove any unwanted colour components which may be present in the light. Alternatively, each of the panels may be illuminated with white light and a respective colouring dye incorporated in the matrix together with the absorbing dye to provide the required colour output.

The invention can be used in combination with any known technique for providing colours.

Dye, either pleochroic or isotropic for example, may also be added to the LC droplets to provide some additional absorption or for the purpose of colouring transmitted light when in its ordered alignment state.

A liquid crystal display device and a projection display system incorporating the device, in accordance with the invention, will now be described, by way of example, with reference to the accompanying drawings, in which:-

Figure 1 is a schematic cross-sectional view, not to scale, through a part of the display device; and

Figure 2 shows schematically the projection display system.

Referring to Figure 1, the display device comprises a liquid crystal display panel 10 and a source of illumination 11 arranged to illuminate the panel from one side. The illumination source 11 may be of any suitable kind, for example one or more miniature

fluorescent light tubes when the device is intended to be viewed directly or a high intensity incandescent lamp when the device is being used as part of a projection system. Here the source of illumination is represented by a tubular fluorescent lamp. The source of illumination may further include a reflector and possibly also a collimator, not shown in Figure 1, for directing light evenly and orthogonally over the input side of the panel 10.

The panel 10 consists of separate, generally spherical, droplets 14 of nematic liquid crystal material dispersed in a solid polymer matrix 15. Only a few droplets are shown for simplicity. The droplets may typically be in the region of 1.0 to 20 micrometres in diameter. On either side of the matrix material 15 are formed transparent, e.g. ITO, electrodes. The electrodes on opposite sides consist of sets of constant width row and column electrodes, 17 and 18 respectively, which at the region of their intersections define individually-operable display elements in an X-Y array. Each of the display elements of the panel is individually controlled using suitable known switching circuitry to provide a respective display effect. Only one complete picture element, here referenced 20, is shown in Figure 1. In a display device suitable for video purposes the total number of display elements provided in the row and column array may be 100,000 or more. The size of each picture element 20 is determined in accordance with the size of the overall display areas of the panel and the required picture element resolution. For video, e.g. TV, display purposes they may be around 10 to 100 micrometres square. In turn the size of the LC droplets used is chosen to suit the picture element dimensions. The thickness of the polymer matrix 15 would be around 2 to 50 micrometres so that several "layers" of droplets 14 can be accommodated, although a single layer of droplets may be used.

The kind of display panel 10 employed in the display device generally follows conventional forms and, accordingly, reference may be made to the aforementioned patent specifications and

articles describing known examples of polymer dispersed devices or encapsulated liquid crystal film devices for further information in respect of its fabrication and operation. Briefly, the liquid crystal droplets are formed and fixed in random dispersement in the polymer film by chemical, thermal or light induced phase separation. The polymer matrix material can be of any type known in the art such as latex, polyvinyl alcohol, epoxy resin, polyurethane resin, polycarbonate resin, polyvinyl butyral resin, etc.. The panel may be one of the encapsulated group in which the liquid crystal is encapsulated in polymer shells which are subsequently embedded in a polymer continuum constituting the matrix or one of the polymer dispersed group in which the liquid crystal droplets are spontaneously dispersed in the matrix material during film formation.

The sandwich structure consisting of the ITO electrodes 17 and 18 and the matrix material 15 containing the droplets 14 are carried on a preferably, although not necessarily, rigid transparent supporting substrate 21, for example of glass or plastics.

In accordance with the invention, the matrix 15 incorporates a light-absorbing dye. This dye is distributed substantially homogeneously and is indicated in Figure 1 by x-shape representations.

In operation of the display device, the display panel modulates light transmitted substantially directly through the panel from the light source 11 in a viewing direction at the output side in accordance with electrical fields established across each picture element by the electrodes 17 and 18, the display elements acting as individual light shutters in controlling the transmission of light. This is achieved by regulating the light scattering characteristic of the liquid crystal droplets.

Considering the display element 20 shown in Figure 1, then in the absence of an electric field across the display element the droplets 14 present in this element are in the isotropic,

non-aligned, phase, with their optic axes randomly oriented and scatter light so that they act to block passage of light from the source 11 directly through the element to the viewing side. Upon the application of an electric field across the element 20 produced by a voltage difference being established between the associated electrodes 17 and 18, represented by closure of the switch 19, the optic axes of the droplets become aligned with the field so that minimal scattering is obtained. In this state, and assuming a suitable choice of refractive indices for the materials, the display element effectively becomes substantially transparent and allows incoming light to be transmitted directly therethrough with practically no change in direction so that a light output is obtained in a viewing direction at the output side of the panel, as represented by the broken arrows in Figure 1. By varying the magnitude of the applied field, the degree of transmission can be varied correspondingly, thereby providing grey scales. Upon removal of the voltage applied to the electrodes 17 and 18, the large surface area to volume ratio of the droplet enables surface interactions to return the nematic droplet to its random alignment state.

The intensity of light escaping from the viewing side of the panel when the droplets of a display element are in their scattering state is reduced by the light absorbing dye present in the matrix. Light is scattered in random fashion so that without the dye a small proportion of the scattered light would tend to pass indirectly through the panel to the viewing side, perhaps via several droplets with the result that the contrast ratio achieved is seriously impaired. The presence of the dye, depending on its concentration, serves to prevent most of the scattered light escaping. Although some light inevitably could still escape from the viewing side in the panel of the invention because of the random nature of the optic axes of the droplets in this state, the amount is comparatively small.

In the aligned droplet state the light still has to travel through parts of the thickness of the matrix material and so will

suffer some loss through absorption by the dye in these parts, although this loss will be minor. Scattered light travels, on average, much further through the matrix material than non-scattered light and accordingly suffers greater losses, even for light which eventually emerges near the normal in the forward direction.

Consequently, the action of the dye results in the contrast ratio being increased at the expense of only a small reduction in the brightness. As an example, it can be expected that the loss to direct (non-scattered) light would be no more than 10 to 20% whereas the resulting loss to the scattered light would be from 50-80%, giving a significant contrast ratio gain. Because the intensity of light scattered sideways by a display element towards adjacent display elements is reduced resolution is improved.

Suitable kinds of absorbing dyes will be apparent to persons skilled in the art. For an illumination source generating white light, the absorbing dye is an effectively neutral, for example black, dye whose concentration in the matrix is such as to provide a relatively weak effect. If, on the other hand, the panel is illuminated with light of a particular colour or colours, a dye having the appropriate colour absorptive characteristics can be used. In order to provide a colour display, a coloured absorbing dye can be used. Even if the illuminating light is primarily of a certain colour, such a coloured absorbing dye can be used effectively to remove unwanted colour components. Such trimming of the spectral transmission serves to increase the colour gamut and eliminates the need for providing separate trimming filters as previously employed in LC display devices before or after the display panel. For the case where the panel is illuminated with white light an absorbing dye having colouring as well as absorptive properties provides a convenient way of achieving a coloured display output.

The combined light output of the display elements of the display device of Figure 1 may be directly viewed by an observer

in the viewing direction. However, in an embodiment of the invention the device is instead used in a projection system to provide an enlarged display. Referring now to Figure 2, there is shown schematically an embodiment of one possible arrangement for a full colour projection system which incorporates three of the above-described display panels which operate to modulate light of the respective one of the three primary colours. Of course, a single display panel may be used in a simpler form of projection system.

The three display panels are referenced at 40a, 40b and 40c and produce respectively coloured outputs which are subsequently combined. Each of the display panels is illuminated from one side with light of a respective primary colour, red, green and blue, and is controlled to act as a matrix light valve to modulate that light in accordance with the picture information so that an image of the picture to be displayed is generated in the respective primary colour at the other, output side, of the display panel.

The differently-coloured images from the three display panels are then optically combined by a combiner 28 comprising cemented glass prisms with dichroic layer applied to mating surfaces into a single multi-colour image beam which is projected by a projection lens 30, shown as a single element for simplicity, to form a synthesised multi-colour picture image on a screen 22 visible to a viewer on the side of screen 22 either facing or opposite the projection lens 30.

The display panels 40a, 40b and 40c are controlled in scanning fashion and are each driven in a conventional manner separately, but in synchronism, by an associated driving circuit (omitted from Figure 2 for simplicity) in accordance respectively with R, G and B video signals.

The particular system shown in Figure 2 employs a single light source, referenced at 50, emitting white light comprising a mixture of red, green and blue chromatic components. Light from the source 50, which may be one or more discharge or incandescent

lamps, is directed with the aid of a reflector 51 and condensing lens 56 into an optical, dichroic, beam splitter 52 which separates the light into three primary colour beams (R, G and B). The green beam passes substantially straight through the beam splitter 52 and is directed onto the display panel 40a to illuminate uniformly and substantially orthogonally the panel by way of a condenser lens 53. The display devices40a, 40b and 40c are arranged at substantially equal distances optically from the beam combiner 28. A folded optical arrangement employing mirrors 54 and 55 is used for the red and blue light beams. The red and blue beams are directed respectively via the mirrors 54 through condenser lenses 53 and substantially uniformly and orthogonally onto the display panels 40b and 40c.

Green light, modulated in accordance with picture information by the display panel 40a is directed into the optical combiner 28. Red and blue light emanating from the display panels 40b and 40c and modulated to constitute red and blue picture image components is deflected into the combiner 28 by way of the mirrors 55. Typical rays for a picture element near the centre of the picture/display panels are indicated in Figure 2 by way of example.

In an alternative arrangement, each display panel could be illuminated by a separate light source producing, possible in conjunction with filters, light corresponding to a respective one of the primary colours.

By virtue of the absorbing dye in each of the display panels, an improved performance in terms of display contrast ratio and resolution is obtained. As previously described, the dye may be an effectively neutral dye or a selective colour absorbing dye, or a combination of both.

In a modified version of the projection system, the display panels may be illuminated with white light and a respective colouring dye added to the matrix material of the display panels.

CLAIM(S)

1. a liquid crystal display device having a liquid crystal panel comprising droplets of liquid crystal material carried in a polymer matrix and electrodes on opposing sides therof defining a plurality of display elements, and means for illuminating the panel from one side, the display elements being operable to control the passage therethrough of light from the illumination means in a viewing direction at the other side so as to produce a display effect, characterised in that the polymer matrix contains a light absorbing dye.

2. A liquid crystal display device according to Claim 1, characterised in that the absorbing dye is a substantially neutral absorbing dye.

3. A liquid crystal display device according to Claim 1 or Claim 2, and wherein the panel is illuminated with white light, characterised in that the polymer matrix further includes a colouring dye for providing a colour output from the device.

4. A projection display system including a liquid crystal display device in accordance with Claim 1 and a projection lens disposed on the opposite side of the panel from the illuminating means for projecting the output from the panel onto a screen.

5. A projection system according to Claim 4, characterised in that the system comprises three liquid crystal display devices whose panels are each illuminated by respectively coloured light and in that the absorbing dye of each device comprises a substantially neutral dye.

6. A projection system according to Claim 5, characterised in that the matrix includes a coloured absorbing dye.

7. A projection system according to Claim 4, characterised in that the system comprises three liquid crystal display devices whose panels are each illuminated by white light and in that the polymer matrix of each device includes a respective colouring dye for providing a respective colour output from the device.

8. A liquid crystal display device substantially as hereinbefore described with reference to, and as shown in, the

accompanying drawings.

9. A projection display system substantially as hereinbefore described with reference to, and as shown in, the accompanying drawings.

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